



■ BIOMECHANICS

Biomechanical evaluation of a novel double rip-stop technique with medial row knots for rotator cuff repair

AN IN VITRO STUDY

**Z. Wang,
H. Li,
Z. Long,
S. Lin,
A. R. Thoreson,
S. L. Moran,
A. Gingery,
P. C. Amadio,
S. P. Steinmann,
C. Zhao**

*Mayo Clinic, Rochester,
Minnesota, USA*

Aims

Many biomechanical studies have shown that the weakest biomechanical point of a rotator cuff repair is the suture-tendon interface at the medial row. We developed a novel double rip-stop (DRS) technique to enhance the strength at the medial row for rotator cuff repair. The objective of this study was to evaluate the biomechanical properties of the DRS technique with the conventional suture-bridge (SB) technique and to evaluate the biomechanical performance of the DRS technique with medial row knots.

Methods

A total of 24 fresh-frozen porcine shoulders were used. The infraspinatus tendons were sharply dissected and randomly repaired by one of three techniques: SB repair (SB group), DRS repair (DRS group), and DRS with medial row knots repair (DRSK group). Specimens were tested to failure. In addition, 3 mm gap formation was measured and ultimate failure load, stiffness, and failure modes were recorded.

Results

The mean load to create a 3 mm gap formation in the DRSK and DRS groups was significantly higher than in the SB group. The DRSK group had the highest load to failure with a mean ultimate failure load of 395.0 N (SD 56.8) compared to the SB and DRS groups, which recorded 147.1 N (SD 34.3) and 285.9 N (SD 89.8), respectively ($p < 0.001$ for both). The DRS group showed a significantly higher mean failure load than the SB group ($p = 0.006$). Both the DRS and DRSK groups showed significantly higher mean stiffness than the SB group.

Conclusion

The biomechanical properties of the DRS technique were significantly improved compared to the SB technique. The DRS technique with medial row knots showed superior biomechanical performance than the DRS technique alone.

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Keywords: Rotator cuff, Suture-bridge, Double rip-stop, Medial row knot, Biomechanics

Article focus

■ This study aimed to compare the biomechanical properties of the double rip-stop (DRS) technique with the conventional suture-bridge (SB) technique and to evaluate the biomechanical performance of the DRS technique with medial row knots.

Key messages

- The DRS technique had superior biomechanical performance compared to the SB technique.
- With additional medial knots, the biomechanical properties of the DRS technique were further enhanced.

Correspondence should be sent to Chunfeng Zhao; email: Zhao.Chunfeng@mayo.edu

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Strengths and limitations

- The quality of the cadaveric rotator cuffs was well controlled. The results are reliable and statistically significant among the three techniques.
- In vivo study is required to investigate the effect of DRS technique with medial row knots on rotator cuff healing.

Introduction

The ultimate goals for rotator cuff repair are to restore integrity, improve function, and relieve shoulder symptoms. While the surgical repair improves patient-reported outcomes,¹⁻⁴ a healed repair showed significantly improved outcomes compared to a non-healed repair.⁵ However, the reported retear rate for large and massive rotator cuff repairs is between 24% and 94%.⁶⁻⁹ Hence, new techniques are being innovated to improve the biomechanical strength of repaired rotator cuff tendon.

Previous studies have shown that rotator cuff repairs using the double-row suture anchor technique have increased repair strength compared to single-row technique.¹⁰⁻¹² However, some clinical studies did not show different functional outcomes between these two techniques.¹³⁻¹⁵ A technique termed suture-bridge (SB) has been advanced to enhance the biomechanical construct.¹⁶ Biomechanical studies using cadaveric shoulders showed that compared with the conventional double-row technique, the SB technique has higher ultimate failure strength and improved contact area.¹⁷⁻²⁰ The in vivo studies also confirmed the SB technique had more effective healing and lower retear rates (6.3% vs 13.5%).^{9,12,21,22} However, during the failure load test most repairs of SB failed by suture cutting through the tendon.^{23,24} The suture-tendon interface turned out to be the weak point of the repaired rotator cuff. Thereafter, many investigators have been focusing on enhancing the initial fixation strength of medial row with different configuration.²⁵⁻²⁸

For these reasons, we developed a novel double rip-stop (DRS) technique for medial row fixation in rotator cuff repair. This repair is designed to more firmly anchor the suture in the tendon and, thereby, enhance repair strength. The first purpose of our study was to compare the biomechanical properties of the DRS technique with the SB technique with respect to footprint area, gap formation, ultimate failure load, stiffness, and failure modes. The second purpose was to evaluate whether the biomechanical performance of the DRS technique could be improved with medial row knots. The hypothesis was that the DRS technique would show better biomechanical performance compared to the SB technique and that the medial row knots would further enhance the biomechanical properties of the DRS technique.

Methods

Shoulder dissection. A total of 24 fresh porcine shoulders were obtained from 12 adult bone mature pigs (mean

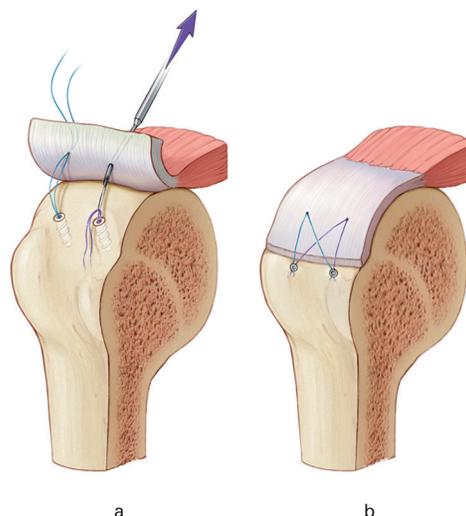


Fig. 1

Schematic configuration of conventional suture-bridge repair. a) Two medial suture anchors (BioComposite Corkscrew FT Anchor 4.5 mm, loaded with No. 2 FiberWire; Arthrex, Naples, Florida, USA) were inserted at the medial row and suture limbs of each anchor were passed through the infraspinatus tendon. b) Two anchors (BioComposite Pushlock 3.5 mm; Arthrex) were used for the lateral row with a knotless technique.

weight 60 kg (SD 12)) that had been euthanized for other Institutional Animal Care and Use Committee-approved studies. Specimens were stored at -80°C and thawed for 24 hours at room temperature before dissection. All soft tissue except the infraspinatus tendon (IST) and muscle was removed from the humeral head. The IST was sharply dissected from its bony insertion to simulate a full-thickness rotator cuff tear.^{10,25,29} The tendon thickness and footprint dimensions at the distal and proximal ends of the bony insertion were obtained with a digital caliper (Johnson Level & Tool Manufacturing Co., Mequon, Wisconsin, USA). The tendon tissues were kept moist using isotonic saline.

Repair preparation and techniques. Two orthopaedic surgeons (ZW and HL) performed all the repairs. Two medial suture anchors (BioComposite Corkscrew FT Anchor 4.5 mm, loaded with No. 2 FiberWire; Arthrex, Naples, Florida, USA) and two lateral anchors (BioComposite Pushlock 3.5 mm; Arthrex) were used for each repair. The rotator cuff tear was randomly repaired by one of three repair techniques: SB repair (SB group), DRS technique (DRS group), and DRS technique with medial row knots (DRSK group).

For the SB group, the SB repair was performed per the manufacturer's instruction. Two medial anchors were inserted 3 mm lateral to the articular margin, 10 mm apart in the superior-inferior dimension, with a 45° deadman's angle.³⁰ The IST was reduced and perforated 12 mm to 14 mm medially by two suture limbs of each anchor (Figure 1a). One suture limb from each of the medial row anchors was secured to the greater tuberosity with two knotless PushLock anchors. The lateral row anchors were inserted 20 mm apart, lateral from the medial anchors

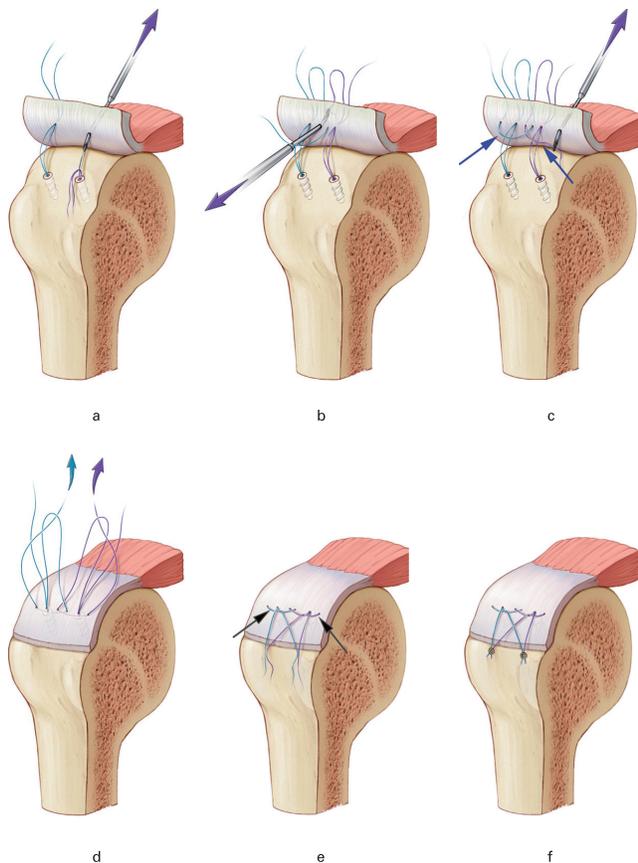


Fig. 2

Schematic surgical procedure for double rip-stop technique (DRS). a) Two screws (BioComposite Corkscrew FT Anchor 4.5 mm, loaded with No. 2 FiberWire; Arthrex, Naples, Florida, USA) were used for the medial row and the sutures were perforated at the tendon at 13 mm to 15 mm medial to the end. b) One suture limb from each anchor was passed through the tendon to form a loop, followed by c) passing the sutures laterally on the articular surface, where the first rip-stop was formed. d) The suture limb was then passed through the loop to form the second rip-stop. e) On the articular surface of the infraspinatus tendon, as well as e) on the bursal surface, two rip-stops were made, respectively. f) Two anchors (BioComposite Pushlock 3.5 mm; Arthrex) were used for the lateral row with a knotless technique. Blue arrows denote the rip-stop of the articular side, and black arrows denote the rip-stop of the bursal side.

(Figure 1b). The sutures were pretensioned before lateral row fixation.

For the DRS group, the medial row anchors were placed as described for the SB repair. After two suture limbs from one anchor were passed through the tendon (Figure 2a), one limb was passed through the tendon from the bursal surface to the articular surface anterolaterally. Thus, a loop was formed on the surface of the tendon (Figure 2b). After passing laterally from the anchor, this limb passed through the tendon from the articular surface to the bursal surface anteromedially (Figure 2c). A rip-stop was formed on the articular surface. Finally, this limb was passed through the loop to create the second rip-stop (Figure 2d). The sutures from the other anchor perforated the tendon in the same way. Thus, two rip-stops were formed on the articular side

(Figure 2c), as well as on the bursal side (Figure 2e). The establishment of the lateral row was the same as for the SB repair (Figure 2f).

For the DRSK group, the technique was almost the same as the technique used in the DRS group (Figures 3a to 3d). After rip-stop was formed on the bursal surface, two square knots were tied for each medial anchor, respectively (Figure 3e). Then the lateral row fixation was established as described above (Figure 3f).

Biomechanical testing. An investigator with a mechanical engineer degree (ART) performed the biomechanical testing. All the repaired specimens were mounted on a servohydraulic test machine (MTS-312; MTS Systems Corporation, Eden Prairie, Minnesota, USA) for mechanical evaluation.³¹⁻³³ The humeri was potted into a plastic tube and positioned to apply a vertical load application in order to simulate physiological load conditions as seen in human supraspinatus tendon. A custom-made clamp gripped the infraspinatus muscle belly and the clamp was frozen by liquid CO₂ to prevent failure at the tendon-grip interface and tissue slippage.^{34,35} The frozen procedure was controlled to prevent the frozen zone extending to the IST. Before biomechanical testing, the specimen was marked at: 1) medially to the medial row; 2) in between both suture rows; and 3) the greater tuberosity.

All specimens were loaded to failure at a rate of 50 mm per minute. Ultimate failure was defined as the peak force observed during loading test. Failure modes were recorded. To assess gap formation and local deformation for stiffness calculations, specimen loading was video recorded (Nikon D3200; Nikon, Tokyo, Japan) throughout the testing.³¹ Videos were processed with image-analysis software ("Image J"; National Institutes of Health (NIH), Bethesda, Maryland, USA) to measure marker displacement and, thereby, determine displacement between the greater tuberosity and lateral row. As 3 mm gap formation was considered as failure for biomechanical study, load to create a 3 mm gap was calculated.^{25,29} Stiffness was calculated from the slope of the linear region of the load–displacement curve.

Statistical analysis. According to one previous study, eight samples per construction was enough to reach 80% power with $\alpha = 0.05$.¹⁰ Continuous data were presented as the mean and SD. One-way analysis of variance (ANOVA) with the Tukey's *post hoc* test was used to compare the footprint and tendon dimension, ultimate failure load, stiffness, and load at 3 mm gap formation among the three repair techniques. The level of significance was set at $p < 0.05$.

Results

Footprint dimensions and tendon thickness. There were no grossly abnormal anatomies in all samples. There was no significant difference among the three groups ($p > 0.05$; one-way ANOVA) regarding the tendon thickness, footprint dimensions, or insertional areas (Table I).

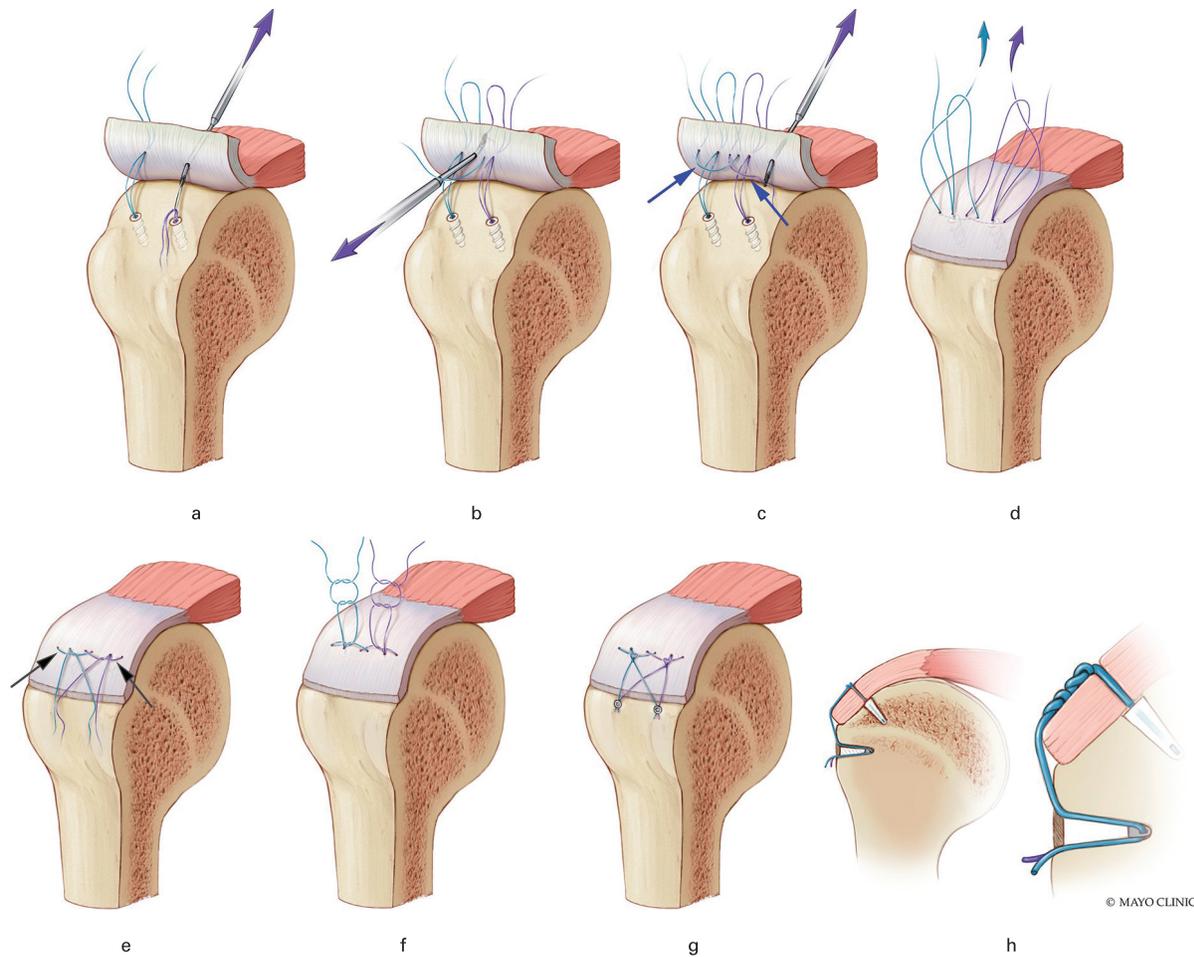


Fig. 3

Schematic surgical procedure for double rip-stop technique with medial row knots (DRSK). a) Two screws (BioComposite Corkscrew FT Anchor 4.5 mm, loaded with No. 2 FiberWire; Arthrex, Naples, Florida, USA) were used for the medial row and the sutures perforated the tendon at 13 mm to 15 mm medial to the end. b) One suture limb from each anchor passed the tendon to form a loop, followed by c) passing the sutures laterally on the articular surface, where the first rip-stop was formed. d) The suture limb then passed through the loop to form the second rip-stop. e) On the articular surface of the infraspinatus tendon, as well as on the e) bursal surface, two rip-stops were made, respectively. e) Two square knots were tied for each medial anchor. f) Two anchors (BioComposite Pushlock 3.5 mm; Arthrex) were used for the lateral row with a knotless technique. g) The enlarged final fixation configuration of DRSK. h) Side view of the configuration of DRSK. Blue arrows denote the rip-stop of the articular side, and black arrows denote the rip-stop of the bursal side.

Table I. Footprint dimensions and tendon thickness for each technique.

| Technique | Mean tendon thickness medially, mm (SD; p-value*) | Mean tendon thickness laterally, mm (SD; p-value*) | Mean footprint width, mm (SD; p-value*) | Mean footprint length, mm (SD; p-value*) | Mean insertional area, mm ² (SD; p-value*) |
|-----------|---|--|---|--|---|
| SB | 3.4 (0.4; 0.654†) | 1.2 (0.1; 0.225†) | 14.3 (1.1; 0.927†) | 19.2 (1.2; 0.862†) | 278.6 (35.0; 0.837†) |
| DRS | 3.6 (0.5; 0.620‡) | 1.3 (0.3; 0.103‡) | 14.5 (0.6; 0.951‡) | 18.9 (1.3; 0.578‡) | 270.9 (22.4; 0.580‡) |
| DRSK | 3.4 (0.3; 0.998§) | 1.2 (0.2; 0.898§) | 14.6 (0.7; 0.781§) | 19.5 (0.8; 0.877§) | 284.5 (13.8; 0.900§) |

*One-way analysis of variance.

†Comparison between the suture-bridge technique and double rip-stop technique without medial row knots groups.

‡Comparison between the double rip-stop technique without medial row knots and double rip-stop technique with medial row knots groups.

§Comparison between the suture-bridge technique and double rip-stop technique with medial row knots groups.

DRS, double rip-stop technique without medial row knots; DRSK, double rip-stop technique with medial row knots; SB, suture-bridge technique.

Load to create 3 mm of gap formation. The mean load to create a 3 mm gap formation between the markers on the medial tendon and the humeri was 82.9 N (SD 24.4; 95% confidence interval (CI) 60.3 to 105.5) for the SB group,

125.8 N (SD 33.8; 95% CI 97.5 to 154.0) for the DRS group, and 120.9 N (SD 43.1; 95% CI 81.0 to 160.7) for the DRSK group. Both the DRS and DRSK groups showed significantly higher mean resistance than the SB group

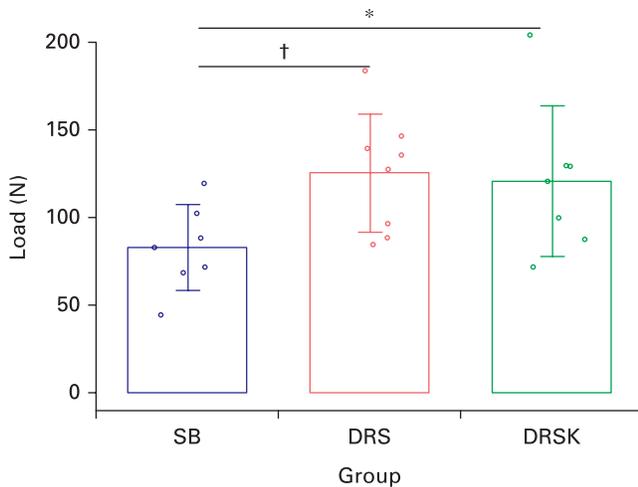


Fig. 4

Comparison of load to create 3 mm gap formation between three techniques (mean and SD). DRS, double rip-stop technique without medial row knots; DRSK, double rip-stop technique with medial row knots; SB, suture-bridge technique. $p < 0.05$. † $p < 0.01$.

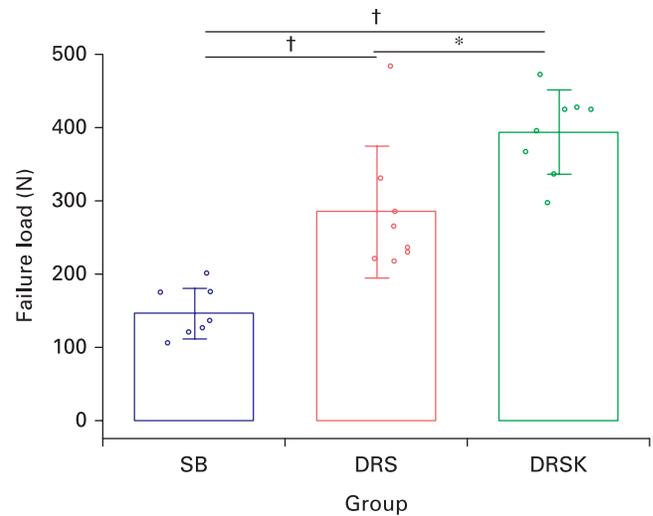


Fig. 5

Comparison of ultimate failure load (mean and SD) of three techniques. DRS, double rip-stop technique without medial row knots; DRSK, double rip-stop technique with medial row knots; SB, suture-bridge technique. $p < 0.01$. † $p < 0.001$.

($p = 0.008$ and $p = 0.033$, respectively; one-way ANOVA). There was no significant difference between the DRS and DRSK groups (Figure 4).

Mode of failure. For the SB group, all specimens failed due to the suture cutting through IST. Four specimens in the DRS group failed due to tendon rupture, three cases failed because the lateral row anchor pulled out from the bone, and one case failed due to the suture being pulled out from the lateral anchor. In the DRSK group, seven specimens failed due to tendon rupture at the medial row and one specimen failed because the suture cut through the medial anchor.

Maximum load to tensile failure. The DRSK group had the highest mean ultimate failure load (395.0 N (SD 56.8; 95% CI 347.4 to 442.5)) compared with the SB group (147.1 N (SD 34.3; 95% CI 118.3 to 175.9; $p < 0.001$; one-way ANOVA)) and the DRS group (285.9 N (SD 89.8; 95% CI 210.8 to 360.9; $p < 0.001$; one-way ANOVA)). The DRS group also showed significantly higher mean failure load than the SB group ($p = 0.006$; one-way ANOVA; Figure 5).

Stiffness. The mean stiffness of the SB group was 14.1 N/mm (SD 4.8; 95% CI 10.1 to 18.1). The mean stiffnesses of the DRS group (19.9 N/mm (SD 6.5; 95% CI 14.5 to 25.3)) and the DRSK group (23.4 N/mm (SD 9.3; 95% CI 15.6 to 31.2)) were significantly higher than that of the SB group ($p = 0.031$ and $p = 0.013$, respectively; one-way ANOVA). No significant difference was observed between the DRS and DRSK groups (Figure 6).

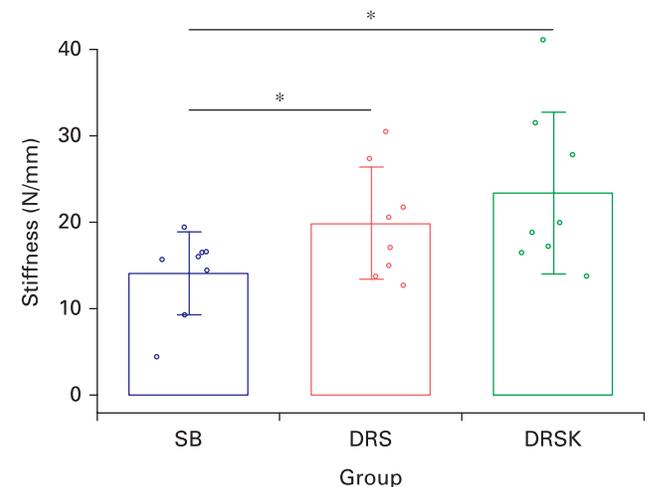


Fig. 6

Comparison of stiffness (mean and SD) of three techniques. DRS, double rip-stop technique without medial row knots; DRSK, double rip-stop technique with medial row knots; SB, suture-bridge technique. $p < 0.05$.

failure load, stiffness, and resistance to gap formation. Furthermore, the repair failure strength of the DRS technique was further enhanced with medial row knots.

The initial biomechanical strength is considered as one crucial factor to promoting the healing after rotator cuff repair. Although SB showed many advantages compared to conventional double row,^{17,20} many clinical studies have reported that the retear rate range of SB was 18.9% to 42.4%.³⁶⁻³⁸ Most repairs of SB failed by the suture cutting through the tendon during the failure load test,^{23,24,29} which demonstrated that the weak point of the SB technique was the suture-tendon interface at the medial row. Thereafter, how to improve the biomechanical strength of suture-tendon interface has become

the research focus in the rotator cuff repair field and a variety of configurations have been developed. One way to improve resistance of the suture-tendon interface is to tie the medial row.^{26,28,39,40} Another technique to limit medial suture cut-through is to create a rip-stop at the medial row.^{23,27,37} These studies showed that with medial row knots or rip-stop, the biomechanical properties, contact area, gap formation, ultimate failure load, and stiffness were significantly improved. However, Smith et al⁴¹ reported that there was no difference in stiffness, ultimate failure load, or total energy to failure between the knotless and knotted techniques. Furthermore, the rate of increase in footprint contact pressure was greater in the knotless construct. Liem et al⁴² found that the SB technique with medial row knots did not affect the blood flow compared with the single-row technique in a sheep rotator cuff repair *in vivo* model. Sun et al⁴³ found that the knots on the tendon side had detrimental effects on the rotator cuff healing. More clinical studies are needed to verify the effect of the medial row knots.

Previous studies have described various rip-stop techniques;⁴⁴⁻⁴⁶ however, these were different from the DRS technique. This is because the DRS technique had not only one rip-stop on the articular surface but also one on the bursal side of IST for each medial anchor. The results confirmed that the DRS technique showed significantly improved biomechanical properties compared to the conventional SB technique, which is consistent with previous research.⁴⁷

During failure testing, the failure modes of the DRS technique with or without medial knots are worth noting. For the SB repair, all samples failed due to the suture cutting through the tendon along with the tendon fibre orientation. However, the IST was ruptured first at the medial row during the failure testing in both the DRS and DRSK groups. This was consistent with our results showing that the DRS technique with or without medial knots significantly improved the resistance to gap formation. Another important point worth noting was that the bone around the lateral row was cut by sutures during the failure test of the samples in the DRS and DRSK groups regardless of failure mode (Figure 7a). When the sutures begin to cut the bone at the lateral row, it not only creates the gap formation at the repair site but also decreases the bone holding strength at the screw interface, which may loosen anchor fixation (Figures 7b to 7d). Therefore, the lateral anchors can be pulled out, resulting in the repair failure. For elderly patients with poor bone quality, this failure mode of the rotator cuff repair may be exacerbated. Therefore, there is a need to overcome this weakening effect by improving the screw anchor system in future.

Our study has several strengths. First, two orthopaedic surgeons (ZW and HL) performed all procedures, and an investigator (ART) with a mechanical engineer degree performed all biomechanical testing. Second, our study showed that the size of porcine IST and original

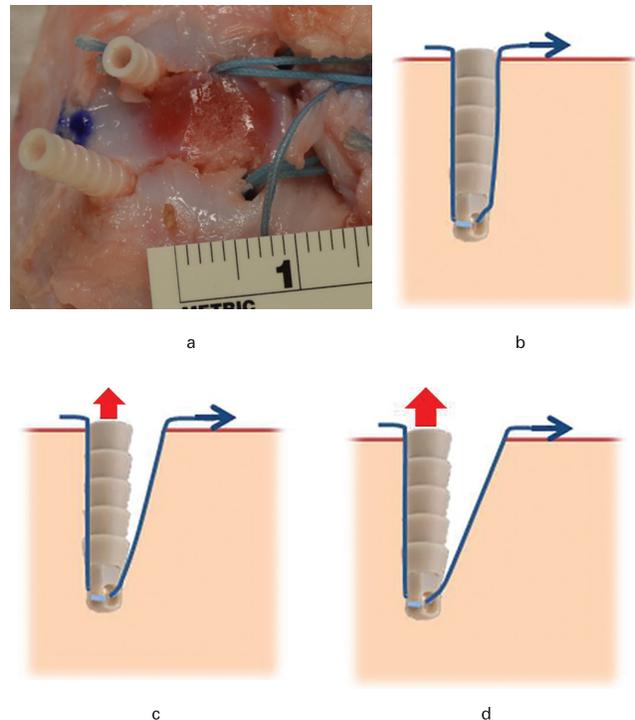


Fig. 7

Schematic illustration of anchor pullout. a) For the double rip-stop without medial row knots (DRS) technique, the lateral anchors were pulled out, whereas the infraspinatus tendon remained intact. b) Before loading, the suture was fixed between the anchor (BioComposite Pushlock 3.5 mm; Arthrex, Naples, Florida, USA) and the bone. c) When the infraspinatus tendon was loaded, the force generated resulted in the suture cutting the bone even further, resulting in a greater reduction in the pullout strength of the lateral anchor. d) With the progressively loading, the gap between the anchor and bone was further increased, so that the lateral anchor was easier to pullout. Red arrows denote the direction of the anchor pullout. Blue arrows denote the force applied on the sutures.

footprint area were consistent among the three techniques (Table I). Third, the pigs used in this study were similar in age and there was no effect of gross evidence of damage or degeneration change on our current study. Fourth, the sizes, as well as the number of sutures, anchors, and PushLock devices were the same for the three techniques.

There are also several limitations in the current study. First, this was a cadaveric study utilizing young porcine IST instead of human tendon. Therefore, the tendon and bone quality are not comparable to aged rotator cuff tear patients. However, porcine shoulder research has been widely used in rotator cuff repair since 1995.⁴⁸ Since the different repair techniques were compared with a relatively uniform model, the comparison should be reliable. Moreover, it is easier to control the tendon quality of the porcine shoulder than human cadavers, as a large percentage of human cadaveric shoulders may have rotator cuff problems.^{49,50} Secondly, we did not measure the contact area or pressure of the repaired rotator cuff. Thirdly, the biomechanical performance was measured at time zero. This study was not able to make

any conclusions about outcomes or healing rates of the tendon repair. Although all the repairs were performed using an open method, the DRS technique with or without medial knots could be done arthroscopically. An in vivo study will be done in the future using open or arthroscopic approaches. Fourthly, the DRS technique is a technically challenging procedure compared to the SB technique, adding operative time and complexity. Finally, only traditional SB with FiberWire was used as a control group. Many of the repair methods currently use the thicker FiberTape, which further adds to the biomechanical strength of the repair. We did not compare our techniques with other modified repairs or suture materials.

In conclusion, this biomechanical study demonstrated that the DRS technique without medial knots achieved superior biomechanical properties compared with the conventional SB repair technique. With additional medial knots, the failure load was significantly improved compared to the DRS technique alone. Therefore, the DRS technique with medial row knots could be a viable option to improve rotator cuff repair.

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Author information:

- Z. Wang, MD, Orthopedic Research Fellow, Department of Orthopedic Surgery, Mayo Clinic, Rochester, Minnesota, USA; Department of Sports Medicine, Xiangya Hospital, Central South University, Changsha, China.

- H. Li, MD, PhD, Orthopedic Surgeon
 - Z. Long, MD, Orthopedic Research Fellow
 - S. Lin, MD, PhD, Orthopedic Research Fellow
 - A. R. Thoreson, MS, Engineer
 - S. L. Moran, MD, Assistant Professor of Orthopedics
 - A. Gingery, PhD, Assistant Professor of Orthopedics
 - P. C. Amadio, MD, Professor of Orthopedics
 - S. P. Steinmann, MD, Professor of Orthopedics
 - C. Zhao, MD, Professor of Orthopedics
- Department of Orthopedic Surgery, Mayo Clinic, Rochester, Minnesota, USA.

Author contributions:

- Z. Wang: Designed the study, Acquired, analyzed, and interpreted the data, Wrote and edited the manuscript.
- H. Li: Designed the study, Acquired and interpreted the data, Edited the manuscript.
- Z. Long: Acquired and analyzed the data, Edited the manuscript.
- S. Lin: Acquired and analyzed the data, Edited the manuscript.
- A. R. Thoreson: Acquired and analyzed the data, Edited the manuscript.
- S. L. Moran: Designed the study, Edited the manuscript.
- A. Gingery: Designed the study, Edited the manuscript.
- P. C. Amadio: Designed the study, Interpreted the data, Edited the manuscript.
- S. P. Steinmann: Designed the study, Edited the manuscript.
- C. Zhao: Designed the study, Analyzed and interpreted the data, Edited the manuscript.

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